Chapter 10
Instrumentation and Monitoring

10-1. Purposes of Instrumentation and Monitoring

a. Many construction contracts for underground works in rock incorporate a geotechnical instrumentation and monitoring program as an integral part of the work. To be successful, such monitoring programs must be carried out for well-defined purposes, be well planned, and be supported by competent staff through completion and implementation of results from the monitoring program.

b. Basic principles of instrumentation and monitoring, as well as details of many instruments, can be found in EM 1110-2-4300, Instrumentation for Concrete Structures.

c. Geotechnical monitoring programs are carried out for one or more of the following purposes:

(1) Where initial ground support is selected based on conditions encountered, monitoring can verify the adequacy of the support and indicate if more support is required.

(2) Early monitoring during construction, perhaps in a test area, can help in planning of later construction procedures or help decide whether contingency plans need to be used.

(3) With the NATM (Section 5-5), monitoring of displacements and loads is an essential part of the construction process, providing input to the ongoing process of design and verification during construction.

(4) In the process of determining the adequacy of ground support, monitoring also serves a safety function, warning of the potential for ground failure.

(5) In some cases, decisions regarding final lining installation can be made based on monitoring whether additional reinforcement or a steel lining may be required.

(6) Monitoring may be required to show compliance with environmental requirements (e.g., groundwater lowering, ground settlements, vibrations) or contractual requirements.

(7) Sometimes data can be obtained that are required or useful for the design of other structures (underground powerhouse, dam, other tunnels in the vicinity).

(8) Monitoring can be used to diagnose flaws in the contractor's procedures and indicate better procedures.

(9) Experimental facilities, pilot tunnels, or shafts that are used to obtain data for design of important structures require special types of instrumentation.

(10) On occasion baseline data may be obtained that will be useful in the long-term operation of a facility (e.g., groundwater pressures).

d. The essential ingredients in a successful monitoring program include the following components:

- Definition of need and objective.
- Planning and design.
- Execution of program.
- Interpretation of data.
- Action based on monitoring results.

All of these components must be carefully planned ahead of time. If the data obtained cannot be properly interpreted in a timely fashion, or if no action is foreseen to be taken based on the data, the instrumentation program will have no purpose and should not be implemented. Many tunnels, especially those bored by TBM through reasonably competent rock, require no monitoring program. Large caverns and near-surface structures are more likely to benefit from monitoring programs. Monitoring of safety-related parameters, such as air quality, methane, or radon concentrations, is discussed in Section 5-13. Environmental monitoring is discussed in Section 5-14.

10-2. Planning and Designing the Monitoring Program

Development of a monitoring program begins with defining the purpose(s) of the program and ends with planning how to implement the measurement data. Systematic planning requires a team effort between the designers of the tunnel or shaft and personnel with expertise in the application of technical instrumentation. Items to consider in planning a successful monitoring program are listed in Table 10-1 and outlined in the following subsections. More comprehensive information is given by Dunnicliff (1988). Specific issues relating to tunnels and underground chamber construction, shafts and portals, and to monitoring in urban environments, are discussed in Section 10-3.

Table 10-1
Items to Consider in Planning a Successful Monitoring Program

1	Define the project conditions
2	Predict mechanisms that control behavior
3	Define the purpose of the instrumentation and monitoring and the questions that need to be answered
4	Select the parameters to be monitored
5	Predict magnitudes of change and set response values for action to be taken
6	Devise remedial actions and arrange for implementation
7	Assign duties and responsibilities for all phases
8	Instrument selection and locations
9	Plan recording of factors that affect measurements
10	Establish procedures to ensure data correctness
11	Prepare instrumentation system design report
12	Plan regular calibration and maintenance
13	Plan data collection and data management

a. Define the project conditions. An engineer or geologist familiar with the project design should be responsible for planning the monitoring program. However, if the program is planned by others, a special effort must be made to become familiar with project conditions including type and layout of the tunnel or shaft, subsurface stratigraphy and engineering properties of subsurface materials, groundwater conditions, status of nearby structures or other facilities, environmental conditions, and planned construction method.

b. Predict mechanisms that control behavior. Before defining a program of instrumentation and monitoring, one or more working hypotheses must be established for mechanisms that are likely to control behavior. Instrumentation should then be planned around these hypotheses. For example, if the purpose is to monitor safety, hypotheses must be established for mechanisms that could lead to rock or support failure.

c. Define the purpose of the instrumentation and monitoring and the questions that need to be answered. Instrumentation should not be used unless there is a valid purpose that can be defended. Peck (1984) states, "The legitimate uses of instrumentation are so many, and the questions that instruments and observation can answer so vital, that we should not risk discrediting their value by using them improperly or unnecessarily." Every instrument should be selected and placed to assist in answering a specific question. If there is no question, there should be no instrumentation. Before addressing measurement methods themselves, a list should be made of questions that are likely to arise during the construction.

d. Select the parameters to be monitored. Table 10-2 gives a list of parameters that may need to be monitored. It is important to consider which parameters are most significant for each particular situation. For example, if the question is "Is the support overloaded?" stress or load in the support is likely to be the primary parameter of interest. However, recognizing that stress is caused by deformation of the rock, it may also be necessary to monitor deformation. By monitoring both cause and effect, a relationship between the two can often be developed, and action can be taken to remedy any undesirable effect by removing the cause.

Table 10-2
Typical Monitoring Parameters

Project Type	Parameter
Tunnels, underground chambers, shafts and portals	Convergence Crown settlement Floor heave Distribution of deformation behind the rock wall Load in dowels and anchors Stress in concrete or steel linings Groundwater pressure within the rock mass Water pressure acting on lining
Urban environments	Surface settlement Vertical and horizontal deformation of buildings and other structures Vertical and horizontal deformation of the ground at depth Groundwater pressure

e. Predict magnitudes of change, and set response values for action to be taken. Predictions are necessary so that required instrument ranges and required instrument sensitivities or accuracies can be selected. An estimate of the maximum possible value or the maximum value of interest will determine the instrument range, and the minimum value of interest determines the instrument sensitivity or accuracy. Accuracy and reliability are often in conflict since highly accurate instruments may be delicate and/or fragile. A predetermination should be made of instrumentation readings that indicate the need for remedial action. The concept of green, yellow, and red response values is useful. Green indicates that all is well; yellow indicates the need for cautionary measures including an increase in monitoring frequency; and red indicates the need for timely remedial action.

f. Devise remedial actions and arrange for implementation. Inherent in the use of instrumentation is the necessity to determine, in advance, positive means for solving any problem that may be disclosed by the results of the observations (Peck 1973). If the observations demonstrate that remedial action is needed, that action must be based on appropriate, previously anticipated plans. Personnel involved in the planning process need to devise remedial action plans for site personnel to follow in the event that response values are reached, and design and construction personnel should maintain an open communication channel during construction so that remedial action plans can be discussed between them at any time.

g. Assign duties and responsibilities for all phases. Duties during the monitoring program include planning, instrument procurement, calibration, installation, maintenance, reading, data processing, data presentation, data interpretation, reporting, and deciding on implementation of the results. When duties are assigned for monitoring, the party with the greatest vested interest in the data should be given direct responsibility for producing it accurately.

h. Selection and location.

(1) Reliability is the most desirable feature when selecting monitoring instruments. Lowest first cost of an instrument should not dominate the selection of an instrument. A comparison of the overall cost of procurement, calibration, installation, maintenance, reading, and data processing of the available instruments should be made. The least expensive instrument may not result in least overall cost because it may be less reliable since cost of the instruments themselves is usually a minor part of the overall cost.

(2) Users need to develop an adequate level of understanding of the instruments that they select and often benefit from discussing the application with the manufacturer's staff before selecting instruments. During the discussions, any limitations of the proposed instruments should be determined.

(3) Choosing locations for the instruments should be based on predicted behavior of the tunnel or shaft. The locations should be compatible with the questions and the method of analysis that personnel will use when interpreting the data. A practical approach to selecting instrument locations involves three steps.

(a) First, identify zones of particular concern, such as structurally weak zones or areas that are most heavily loaded, and locate appropriate instrumentation.

(b) Second, select zones (normally cross sections) where predicted behavior is considered representative of behavior as a whole. These zones are regarded as primary instrumented sections. Instruments installed in these zones will provide comprehensive performance data.

(c) Third, because the primary zones may not be truly representative, install simple instrumentation at a number of secondary instrumented sections to serve as indices of comparative behavior. If the behavior at one or more of the secondary sections appears to be significantly different from the primary sections, additional instruments can be installed at the secondary section as construction progresses.

i. Record factors that affect measurements.

(1) For proper interpretation of virtually all site instrumentation data, it is essential to monitor and record all site activities and climatic conditions that can have an effect on the measurements obtained. These include at least the following:

- Progress of excavation (e.g., distance of advancing tunnel face from installation).
- Excavation of adjacent openings, including effects of blasting.
- Installation of lining or other ground support.
- Installation of drains or grouting.
- Unusual events (ground instability, excess water inflows, etc.).
- Continued monitoring of groundwater inflow into the underground space.

(2) Usually, variations in the geology or rock quality have a great effect on monitoring data. While it is generally recommended to map the geology along an important underground facility during construction, it is especially important in the vicinity of extensive monitoring installations.

j. Establish procedures to ensure data correctness. Personnel responsible for monitoring instrumentation must be able to answer the question: "Is the instrument functioning correctly?" They can sometimes determine the answer through visual observations. In critical situations, more than one of the same type of instrument may be used to provide a backup system even when its accuracy is significantly less than that of the primary system. For example, an optical survey can often be used to examine correctness of apparent movement at surface-mounted heads of instruments installed for monitoring subsurface deformation. Repeatability can also give a clue to data correctness. It is often worthwhile to take many readings over a short time span to determine whether a lack of normal repeatability indicates suspect data.

k. Prepare instrumentation system design report. An "Instrument System Design Report" should be written to summarize the planning of all previous steps. This report forces the designer to document all decisions, at which point they can be reviewed to ensure that they meet the needs of the project.

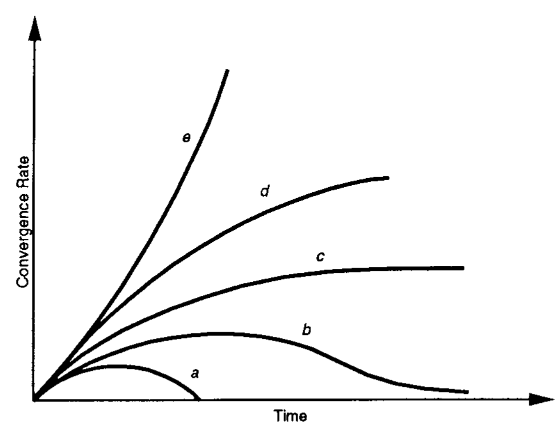
l. Plan regular calibration and maintenance. Regular calibration and maintenance of readout units are required during service life. During the planning process, the instrumentation designers should develop procedures and schedules for regular maintenance of field terminals and accessible embedded components.

m. Plan data collection and data management. Written procedures for collecting, processing, presenting, interpreting, reporting, and implementing data should be prepared before instrumentation work commences in the field. The effort required for these tasks should not be underestimated. Computerized data collection, processing, and presentation procedures have greatly reduced personnel effort, but limitations remain. No computerized system can replace engineering judgment, and engineers must make a special effort to ensure that data are interpreted and reported and that measured effects are correlated with probable causes.

10-3. Monitoring of Tunnel and Underground Chamber Construction

The behavior of a tunnel opening is most drastically manifested in the displacements of the tunnel walls and the rock mass surrounding the tunnel. Convergence of the tunnel walls is by far the most important indicator of tunnel performance and is also relatively easy to measure. Loads, strains, and stresses are generally more difficult to measure, and more difficult to interpret.

a. Displacement and convergence. The absolute value of tunnel convergence can sometimes be predicted, and exceeding this value could be cause for concern; however, the rate of convergence is the more important parameter to watch. Figure 10-1 shows conceptually several time plots of rate of convergence. Curves a and b show decreasing convergence, indicating eventual stability of the structure. If the convergence rate reaches zero, a final lining installation in the tunnel thereafter would receive no load. If the displacement approaches an asymptotic value, the load on the final lining can be reduced by delaying its installation. Very often the time-dependent displacement varies linearly with the log of time, and plots of displacement versus log time can be used to predict long-term performance. Nonuniform convergence is evidence of potential nonuniform loads on a permanent lining. Loads can be inferred from the displacements by back calculation using assumed uniform or nonuniform load distributions so that loads can be compared with those assumed for design, and the adequacy of design can be assessed.



Curves *c, d, e* with increasing convergence rates generally indicate unacceptable performance.

Figure 10-1. Tunnel convergence rates

(1) The most common convergence measurement is one taken across the horizontal diameter. Vertical measurements are not usually taken due to interference with equipment and traffic. Diametral measurements are also possible. TBM equipment often prevents or seriously hampers attempts at convergence monitoring. In such instances, precision surveying using total stations and reflector targets may be a practical solution. A typical type of response to overstress in a tunnel with a level floor in weak ground such as a clay shale is excessive floor heave.

Monitoring of floor heave is difficult because of traffic and softening due to water flow. Measuring points can be set a distance below the top of the floor and protected, and read with high-precision electronic leveling.

(2) It is often necessary to determine the depth of rock damaged by blasting and the depth of inelastic or creep deformations behind the wall of a tunnel or an underground chamber. Such measurements are especially useful if convergence estimates were part of the basis for ground support or lining design, and if the elastic and inelastic parts of convergence must be differentiated. Data on ground movements behind the tunnel wall are usually obtained using multiposition borehole extensometers (MPBXs). Anchors are attached to the walls of a radially drilled borehole at various distances from the wall. These anchors are connected to a measuring device at the wall that permits a determination of relative displacements between the anchorage points. Comparing such data with theoretical elastic or elastoplastic displacement variations, it is possible to derive parameters for elastic and plastic analysis, and to determine the extent of plastic displacement. This can be important for determining the required depth of dowels or rock bolts. In most tunnels, such measurements would be used only in areas of severe displacements, or for a typical test section, where the data may be applicable to a great length of tunnel. MPBXs are usually more useful in large, complex rock chambers. Where pillars are left between adjacent tunnels, or rock noses left at tunnel wyes, MPBX installations can be used to assess the degree of overstress or the stability within the pillar or nose, as manifested by displacements.

b. Load measurements. In past years, when extensive steel set support was common in tunnels, load cells were often incorporated in selected steel sets. Sometimes load cells were installed between steel sets and the ground to measure loads in and on steel sets to verify design assumptions and add to the database for design of steel sets. These types of measurements are usually not successful, because the presence of the instruments affects the loads measured. A better alternative is to equip steel sets with sets of strain gages for determining strains and loads in the sets. More common are load cells to measure loads on rock anchors in critical tunnel locations. Data from such installations can indicate if anchors need to be supplemented because of excessive loads. Such measurements are beneficially supplemented with MPBX installations to indicate the seat of any ground movements to which high loads may be ascribed. Anchor load cells are primarily installed on tensioned anchors in important large underground chambers.

c. Stress and strain measurements. Strain gages can be embedded in a tunnel lining of shotcrete or cast-in-place concrete to determine stresses and loads within the concrete; however, these installations often fail in their ultimate purpose because strains that occur during curing due to temperature and shrinkage mask the effects of the subsequent stressing of the concrete. Strain gage installations on lattice girders embedded in shotcrete have been more successful. Strain gages have also been used to measure strains in the steel lining of a pressure tunnel. Such measurements can track the performance of the lining in the long term, for example, where nonuniform effects of squeezing or swelling ground or fluctuating groundwater pressures are expected.

d. Measurement of groundwater pressure. There are many instances where groundwater pressures, or the depth of the groundwater table, require monitoring. Piezometers to measure groundwater pressure can be installed in boreholes from the ground surface but can also be installed from within a lined structure or in holes drilled from underground chambers. Examples of situations requiring groundwater monitoring are as follows:

(1) Where groundwater resources must be protected for environmental or economical reasons and the tunnel could act as a drain.

(2) Where groundwater lowering could result in unacceptable formation compaction or consolidation, resulting in ground surface settlements.

(3) Where tunnel leakage could propagate through the rock mass and cause seepage into a powerhouse or slope stability problems in an adjacent valley.

e. Monitoring of shafts and portals.

(1) Portals in rock can suffer instability in the same way as excavated slopes. Loose rock can fall; shallow or deep-seated failures can develop along more-or-less circular slip surfaces or along planes of weakness. Tension cracks can open a distance above the face of the portal slope; if filled with water, such cracks are potentially dangerous because they add to the driving force of a failure mechanism. Portals and slopes, as well as vertical excavated walls, are usually monitored using the following types of installations:

- Settlement points above the slope.

- Survey points or survey reflectors on the face of the slope.

- Inclinometer casings installed vertically from above the slope, probed by inclinometers.

- Horizontal or slightly inclined MPBXs installed from the face of the slope or portal face.

- Monitoring of surface exposures of rock fractures to determine if movement occurs along the fractures.

(2) In general, shafts can be monitored using the same types of devices as tunnels, including convergence measurements and MPBXs. Displacements of large-diameter shaft walls through low-strength overburden are sometimes monitored using inclinometers and other devices, similar to slopes and portals.

f. Monitoring in urban environments. Monitoring of shaft and tunnel construction in urban areas is generally conducted to meet specific environmental requirements and measure environmental effects. In areas of existing structures and utilities, displacements due to tunneling or shaft construction can cause damage. Underground structures in rock do not usually cause undue surface displacement; but on occasions, dewatering occurring during construction can cause consolidation of soft or loose sediments. In such cases, settlement monitoring using surface settlement points, piezometers to measure effects on groundwater pressures, and sometimes inclinometers around shafts may be useful to diagnose unacceptable performance and determine remedial measures. Several other types of monitoring are often required for various environmental purposes, as outlined in Section 5-14. These may include the following general types:

(1) Monitoring of vibrations due to blasting (see Section 5-2) or due to TBM operation.

(2) Monitoring of dust and noise transmitted to habitations in the vicinity due to construction activities and related construction traffic.

(3) Monitoring the chemical quality and silt content of the effluent water from the construction site; discovery of pollutants encountered in excavated materials or pumped water.

(4) Monitoring of air quality in general.

g. Data collection and interpretation. Personnel should take the first step in determining whether the instrument data are accurate and the instrument is functioning correctly by comparing the latest readings with previous readings. From this comparison, the personnel can identify any significant changes. If response values have been reached, the plan for remedial action should be implemented. During data collection, all factors that may influence measured data should be recorded and damage, deterioration, or malfunction of instruments noted. The first aim of data processing and presentation is to provide a rapid assessment of data to detect changes that require immediate action. Data collection personnel are usually responsible for this task. The second aim is to summarize and present the data to show trends and compare observed with predicted behavior to determine the appropriate action. After data have been processed, plots of data are prepared with plots of predicted behavior and causal data often included on the same axes.

h. Interpretion of data. The method of data interpretation is guided by the original purpose for the monitoring program. Communication channels between design and field personnel should remain open. Design engineers who framed the questions that need to be answered should continue to interact with the field engineers who provide the data. The data should be evaluated to determine reading correctness and to detect changes requiring immediate action. Data readings must be correlated with other factors to determine cause and effect relationships and to study the deviation of the readings from the predicted behavior. When faced with data that, on first sight, do not appear to be reasonable, there is a temptation to reject the data as false. However, such data may be real and carry an important message. A significant question to ask is: "Can I think of a hypothesis that is consistent with the data?" The resultant discussion, together with the procedures used for ensuring data correctness, will often lead to an assessment of data validity.